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T-ADC(X) Maneuvering in Waves Study Using FREDYN

by
Timothy C. Smith

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This report details the maneuvering in waves capability for Underway Replenishment (UNREP) of the T-ADC(X) cargo ship. It contains a description of software and computer ship models used; a synopsis of the investigation methodology; and the results of the computer study. The results include course deviation, motions (heave, roll, pitch, yaw), as well as rudder size required to maintain heading at UNREP speeds. These data are presented as speed-heading contour plots and/or tabular form in the report.

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ABSTRACT

This report details the maneuvering in waves capability for Underway Replenishment (UNREP) of the T-ADC(X) cargo ship. It contains a description of software and computer ship models used; a synopsis of the investigation methodology; and the results of the computer study. The results include course deviation, motions (heave, roll, pitch, yaw), as well as rudder size required to maintain heading at UNREP speeds. These data are presented as speed-heading contour plots and/or tabular form in the report.

ADMINSTRATIVE INFORMATION

This task was performed at the Naval Surface Warfare Center, Carderock Division (NSWCCD) by the Seakeeping Department (Code 55). This work was sponsored by the Naval Sea System Command (NAVSEA O3D1) under Project Element 63564N, Project Number S040800, and authorized by Work Request N00024989WR10661-AA.

BACKGROUND

The purpose of this study is to determine the course keeping performance in waves of the T-ADC(X) point design. The T-ADC(X) is a dry cargo ship for underway replenishment (UNREP) of fleet ships. The main concern is the ability to maintain heading in a seaway; this is critically important for UNREP ships. The UNREP requirement is to maintain heading in sea state 5 at 14 knots.

This study used the FREPOLAR computer program to model the course keeping performance in waves of the T-ADC(X) point design. The sponsor provided point design information sufficient to develop the FREDYN[1] input and computer model. The sponsor already has a calm water maneuvering assessment of the T-ADC(X) point design. The proper autopilot gains were determined as the first step by finding coefficients to maintain heading at worst heading, i.e., usually bow quartering. The autopilot gains, or coefficients, determine the relative importance of the various terms in the autopilot control law.

Then, using FREPOLAR, the investigator performed sufficient computer runs to determine performance of point design in sea state 5 as a function of speed and heading. The study examined course keeping in terms of horizontal motion (xy) and heading. The study considered speeds of 10 to 16 knots in 2 knot increments and headings 0-180 in 15 degree increments. Additionally, the study investigated rudder size effects on maneuvering performance, if needed.

Reference 2 gives motion criteria and limits for UNREP operations. The motion criteria deal mainly with cargo handling and loading, crew stumbling in terms of lateral and vertical acceleration; and ship slamming and deck wetness. Considering the size of the T-ADC(X), ship accelerations, slamming, and deck wetness are not deemed

problematic. The limits for cargo handling are: 5 deg of roll and 2 deg of pitch. Both roll and pitch are single significant amplitudes (SSA). For the purpose of this study, longitudinal and lateral course deviations, surge and sway, greater than 15 meters are considered unacceptable.

FREDYN AND FREPOLAR DESCRIPTION

FREDYN[1] is a time domain seakeeping program used to evaluate the motion response of a steered ship in moderate to extreme waves and wind. It can also be used to evaluate maneuvering characteristics in calm water and waves.

To model UNREP conditions adequately necessitates taking into account various non-linearities. The approach used by FREDYN is a combination of theoretical and empirical approaches, rather than purely theoretical, with all physically relevant factors considered in a straightforward manner. Empirical viscous flow forces are added to the strip theory potential flow solution to complete the physical model. FREDYN takes into account above waterline geometry in calculating large amplitude wave hydrostatics and excitation.

FREDYN is only valid for monohulls, at this time, for speeds of zero to 0.5 Froude number. The waves are modeled using linear superposition for long crested, irregular, deep water waves that can be steep, but not breaking. The waves can come from an arbitrary heading. Alternatively, sinusoidal regular waves can be specified.

FREDYN does not account for any dynamic water-on-deck or bulwark submergence effects. There is a damaged stability option, which does allow dynamic flooding of compartments.

FREDYN was developed by the Maritime Research Institute Netherlands (MARIN) and is proprietary to Cooperative Research Navies (CRNAV) members.

FREPOLAR is a program shell that makes multiple FREDYN runs for a user-defined set of speeds, headings, and sea conditions. It does some post-processing to determine number of broaches, surf riding, and capsizing events based on user defined criteria. For this study, it was modified to output longitudinal and lateral course deviation, denoted "surge" and "sway", respectively. Each FREPOLAR run uses the same random seed number for every FREDYN run made during the FREPOLAR run. A random seed number is the number used to start a random number generator. The same random seed number will produce the same set of random numbers every time and for this application the same wave time history every time.

HULL FORM DESCRIPTION

The version of the T-ADC(X) hull form that was used for this study is a relatively full form, high beam to draft ratio dry cargo ship with a bow bulb and tunnel stern. The ship has a single propeller and its shafting is enclosed by a large producible centerline skeg. See Table 1 for principal dimensions and loading conditions.

FREDYN uses 21 equally spaced stations to define the hull form. The sponsor's representative (Nichols Advanced Marine Enterprises) provided the hull offsets as well as

appendage information. The bilge keel was assumed to be one third the length between perpendiculars centered at midships and 1 meter wide. There was no additional skeg added for viscous effects.

The bow stem above the bow bulb was increased from 0 mm to a half breadth of 30 mm to avoid numerical problems within FREDYN. Additionally, the keel position at the aft perpendicular was placed lower in the water by 29 mm so each station would have some wetted surface at the design draft. Considering the size of the T-ADC(X) these changes have a negligible effect on the results. See Figure 1 for the body plan used in the FREDYN simulation.

AUTOPILOT DESCRIPTION

FREDYN uses a Proportional-Integrative-Derivative (PID) controller with sway, roll, and yaw terms as the autopilot. The autopilot coefficients determine the response of the rudder based on the position and motion of the ship. This controller used only yaw and yaw rate. Surge or sway were not explicitly controlled.

Four controllers were investigated, three human navigators and one "perfect" autopilot. The human navigator controller values were determined from analysis of full scale trials data of a larger Coast Guard cutter under manual control[3]. The "perfect" autopilot controller values are considered optimistic, though it seemed reasonable to use the best helmsman when conducting Underway Replenishment (UNREP). Initial runs were made using the three human navigators' coefficients and the best one chosen, number 2. See Table 2 for an example of the response as a function of controller.

The study used typical numbers for maximum rudder angle, 35 degrees, and maximum rudder rate, 3 deg/sec, in the absence of actual machinery values. The autopilot coefficients used were determined from full-scale trials of the 378 foot Coast Guard High Endurance Cutter with a human pilot. The yaw and yaw rate coefficients were determined by regression analysis of the yaw and rudder angle channels. The autopilot only controlled heading. See Table 3 for the coefficients used for the different controllers.

CONDITIONS

The study made sufficient FREDYN/FREPOLAR runs to determine performance of point design in sea state 5 as a function of speed and heading. The study examined course keeping in terms of horizontal motion (surge/sway) and heading. There were two parts to the study: the calm water maneuvering and maneuvering in waves. The loading condition investigated was the full load mixed cargo.

The calm water maneuvering are not an extensive study, but simply provide points for comparison with the existing calm water maneuvering predictions. Only turning circles were done as the calm water maneuver. The speeds were 5 through 20 in 5 knot increments.

The maneuvering in waves study considered speeds of 10 to 16 knots in 2 knot increments and wave headings 0-180 in 15 degree increments. Rather than the median sea state 5 wave height of 3.25 m, the study used the maximum value of 4 m to ensure complete operability at sea state 5. Results are the combination of four one simulated hour FREPOLAR runs.

Additionally, using just one FREPOLAR run, the study investigated low and medium sea state 5 response. The maneuvering effect of a 20% larger rudder size was studied as well. The larger rudder maintained the same aspect ratio as the original rudder.

CALM WATER RESULTS

The FREDYN calm water maneuvering results are only tactical turning circles at speeds of 5, 10, 15, and 20 knots. The T-ADC(X) starts with an initial velocity and the rudder is turned over to the maximum rudder angle, 35 degrees, at the maximum rudder speed, 3 degrees/sec. The rudder is left at that angle for the remainder of the run. The run lasts until the T-ADC(X) achieves a steady state turning diameter. Table 4 provides a comparison for the existing calm water maneuvering predictions. This study did not make that comparison.

Advance is the distance along the original course from where the rudder is initially turned to the point where the heading is perpendicular to the original course. Transfer is the distance perpendicular to the original course from where the rudder initially turns and to the point where the heading is perpendicular to the original course. See Reference 4 for a more complete description of maneuvering definitions.

MANEUVERING IN WAVES RESULTS

To ensure full operability through sea state 5, the maximum significant wave height and most probable period were chosen. The seaway was described using a Bretschneider spectrum with 4 m significant wave height and 9.7 second average period. For comparison medium and low sea state 5 runs were made at 3.25 m and 2.5 m respectively. The average period was 9 seconds for both sea conditions. Runs were made for speeds from 10 to 16 knots at headings from 0 to 180 in 15 degree increments. Results were considered symmetric port and starboard.

Because FREDYN/FREPOLAR is a time domain model each run is only one possible representation of an infinite number of possible finite time histories for a given spectra. The random seed number determines that representation. The seed values used were known to produce capsizing events in other studies. The choice of seed number does not appreciably affect the results, except surge, due to the long simulation time causing the statistics to average out as time goes to infinity. There is less variation in the significant single amplitudes than the maxima for response other than surge.

As an example, see Table 5 for trends at 12 knots and worst heading. Table 6 shows trends at 12 knots and stern quartering seas (135 degrees). The high sea state 5 results presented are the combination of four FREPOLAR runs with four different seed values into one run for analysis purposes. The combined significant single amplitude

values are based on the concatenation of the four runs; the maximum values are the maximum of all four runs.

Surge and sway include long period maneuvering oscillations as well as wave induced short period oscillations. The maneuvering oscillations are a function of the interaction between the controller and individual wave groups. As such, an hour run has fewer samples of these oscillations than say roll. This is why there is more variation in surge and sway than other responses, such as yaw. Therefore, longer runs are necessary to generate enough samples for the runs to be statistically "equal". Looking at short period response, like yaw, show an hour is enough time for those channels to be statistically equivalent.

SIX DEGREE OF FREEDOM RESPONSE

FREDYN calculates the six degree of freedom response of the T-ADC(X) in waves. For the purposes of UNREP maneuvering concerns, only surge, sway, and yaw are of interest. The other motions, heave, roll, and pitch, are compensated for by the constant tension winches. Heave, roll, and pitch play a role in UNREP in terms of cargo strike-up, strike-down, and handling.

Figures 2-7 are contour plots of the six degree-of-freedom response detailing the UNREP speed-heading conditions. Tables 7-18 are the numerical values output from FREPOLAR and used to generate the contour plots. The term "absolute maximum" means the value is the absolute value of the greater of the positive or negative maxima.

Surge and sway in this study include course deviation as well as wave induced oscillations. So large significant and maximum values should not be interpreted as a single wave induced event. Rather, they indicate the degree of difficulty in maintaining a constant speed and heading. Examining single FREDYN runs shows wave induced oscillations on the order of 2-5 meters overlaid on a much larger, slow period oscillation. The slow period oscillations were on order of 20-30 minutes. Obviously, a better helmsman (control law) would improve the slow period oscillations.

As such, surge and sway single significant amplitude are less than 15 m for speeds 10-16 knots and headings forward of beam seas. This also corresponds to the region of low heave, roll, and yaw. Pitch is slightly larger in bow seas, but pitch values are less than 2 degrees for all conditions examined. Sway and yaw are near zero for head and following seas because the simulation used long crested waves.

This region of low response is consistent with UNREP operational guidance of operation in head to bow seas. Given the operability criteria mentioned earlier, the T-ADC(X) has complete operability in this region.

Response tends to be better with increased speed for bow wave headings and worse in quartering seas, i.e., aft of beam. In fact, the worst surge, sway, and roll occur at 16 knots at 150-180 degree headings. Operators avoid these conditions for just that reason.

Extreme events

In addition to normal maneuvering, FREDYN also predicts the occurrence of extreme events such as capsizing, broaching, and surf riding. Broaching is a large uncontrolled yaw accompanied by a large increase in yaw rate. Surf riding is defined as the combination of ship speed in excess of speed due to propeller <u>and</u> very small rotational rates for more than 1.5 seconds. The T-ADC(X) hull form had no occurrences of any of these extreme events in all the runs made.

Typically, surf riding is defined as either excessive speed <u>or</u> near zero response. Initial runs with the T-ADC(X) indicated many false instances of surf riding due to the slow rotations of the hull form causing it to appear to have near zero rotational rates. Consequently, the definition of surf riding became the simultaneous occurrence of excess speed and very small rotational rates.

LOW AND MID SEA STATE 5

The response of the T-ADC(X) in low to mid sea state 5 shows the affect of increasing sea state on operability. Whereas complete operability through sea state 5 is desired, it may be useful to see the response at lesser sea conditions. The significant wave heights are 2.0 and 3.25 m for the low and middle sea states. In both cases, the average period was 9.0 seconds. This is a slight reduction in period to reflect the smaller waves heights. Only one FREPOLAR run was made for each condition. The runs used "#2 human" controller coefficients and random seed #2.

Tables 19-21 show the significant single amplitude (SSA) for horizontal motions by sea state at the worst heading. Tables 22-27 show the SSA and absolute maximum for horizontal motions in low sea state 5. Tables 28-33 show the SSA and absolute maximum for horizontal motions in middle sea state 5. Figures 8-16 show surge, sway, and yaw SSA for the speed-heading range. The important point to remember is these results are for one seed number, i.e., one seaway representation. As such, they provide a relative comparison. Many FREPOLAR runs with different seed numbers are necessary to calculate statistically valid results.

The changes with respect to speed are a combination of effects. The larger values at 10 kn show the rudder lacks enough lift to maintain heading. Examining Tables 34-36, show the larger rudder with more lift improving performance at the lower speeds. The relatively small change in the 16 kn column of Tables 34-36 indicate the cause is not associated with the rudder. The larger values at 16 kn result from approaching zero encounter frequency and the greater possibility of near broaching and surf riding.

The response does increase with wave height. Even at worst heading, sway and yaw values seem acceptable through mid sea state 5. Surge has large values even at low sea state 5. The large surge values tend to be a result of long period oscillation rather than short period wave induced oscillations. As such, throttle, as well as, better rudder control could help the situation. Also Tables 22-23 and 28-29 show relatively small surge values with only a few large peaks. This indicates acceptable course control over most of the speed-heading range throughout sea state 5.

RUDDER SIZE

The study also increased rudder area 20% to increase operability and highlight control law effects. Hopefully, the larger rudder would demonstrate a potential operability benefit. It would also show how much of an increase in area is necessary to create a change. Also the larger rudder would exaggerate any deficiencies in the controller law. Tables 34-36 show the comparison of the original and 20% larger rudder at the worst heading. Tables 37-42 show the horizontal motion results for all speed-heading combinations in the study. Figures 10, 13, and 16 show surge, sway, and yaw, respectively, for the larger rudder over the speed-heading range.

The increased rudder size does decrease sway and yaw. Surge, except at 10 kn, is largely unaffected. Surge tends to be smaller in bow seas and greater in stern seas; with an overall increase across speeds-headings. This is not surprising, considering a rudder not used to control longitudinal motion. This indicates a throttle controller would be necessary to reduce longitudinal course deviation (surge).

The surge increase at 14 kn with the larger rudder is a result of comparing different headings. The larger rudder value is for 30 degrees off the stern rather than 45 degrees, so that there is more longitudinal excitation at the larger rudder heading. The worst speed-heading combination varies due to the time domain interaction of different rudder effects. The effect of a larger rudder is small indicating the design rudder size is reasonably good.

SUMMARY

The T-ADC(X) maneuvering study investigated six degree of freedom response in high sea state 5 sea conditions at typical UNREP speeds. The study considered long crested waves from any direction. The high sea state 5 results presented, unless otherwise noted, are the combination of four one-hour simulation FREPOLAR runs.

The surge and sway results include long period course deviations as well as shorter period wave oscillations. Large surge and sway values indicate difficulty in maintaining a constant speed and heading. Actual wave induced oscillations, not including course deviation, are on the order of 2-5 meters.

Yaw also tends to have a non-zero mean value, indicating a long period maneuvering influence. The long period maneuvering influence increases the yaw significant values because the long period oscillations were not removed from the time history before analysis. Even so, approximately 90% of the speed-heading matrix has values less than 4 degrees.

Single significant amplitude pitch is less than 2 degrees for the entire speed-heading matrix. Single significant amplitude roll is less than 5 degrees bow wave headings less than 80 degrees and stern headings greater than 160.

Using criteria from Reference 2, the combination of the lowest motion areas indicates acceptable UNREP operations at head to beam seas at 14-16 knots. Speeds from 12-10 knots have similar operability from head to 65 degree seas off head.

Increasing the rudder area 20% does not increase performance appreciably. This indicates the present rudder size is adequate for navigation. Effort should be focused on better use of the rudder, rather than increasing its size.

The effect on maneuvering on longitudinal and lateral course deviation, surge and sway, is a function of the interaction between the controller and individual wave groups. Statistically, this makes the phenomenon less common than other response, e.g., roll oscillation. As a result, more FREPOLAR runs with different seed numbers are necessary to generate statistically valid results.

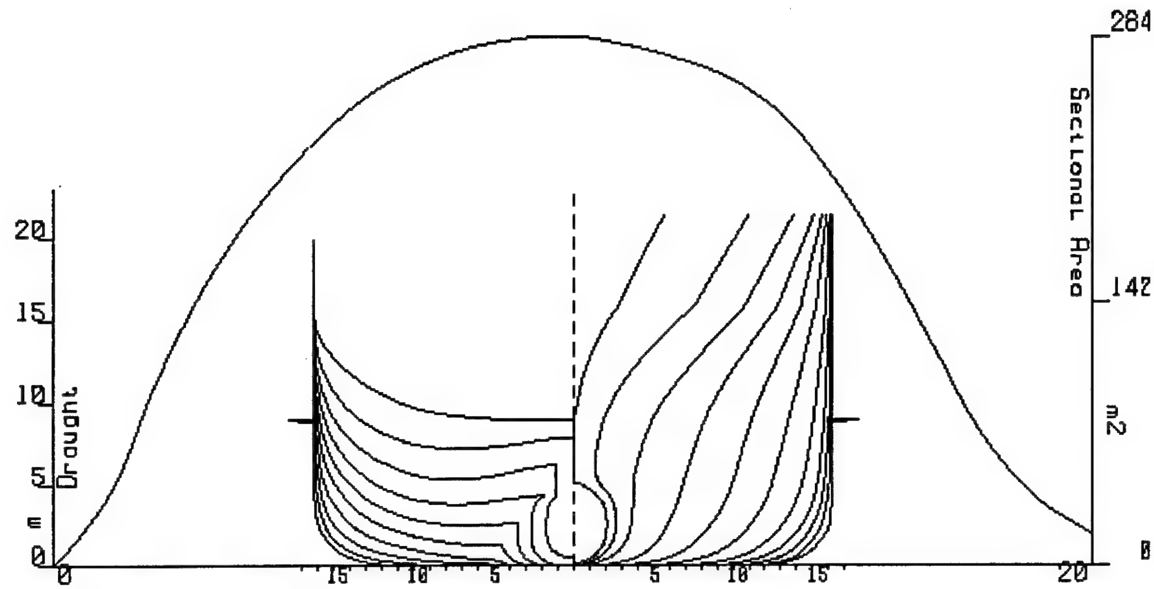

Figure 1. T-ADC(X) (version 112b) body plan and sectional area curve used by FREDYN.

Table 1. T-ADC(X) principal dimensions and loading conditions.

length overall,	210 m			
length between perpendiculars,	203 m			
beam,	32.3 m			
loading conditions	FL mixed	FL stores	Max Weight w/ service life	Arrival
displacement (normal, heavy, and light),	36525	34462	38648	24726 MT
draft	8.33	7.94	8.72	6.21 m
draft (fwd),	7.86	7.14	7.96	3.68 m
draft (aft),	8.7	8.6	8.72	8.48 m
block coefficient	0.652	0.646	0.659	0.592
waterplane coefficient	0.799	0.794	0.804	0.755
midship section coefficient,	0.979	0.978	0.98	0.972
BMt	10.68	11.073	10.314	13.308 m
KB,	4.538	4.323	4.757	3.385 m
KG with .3 m FS correction	12.55	12.62	12.69	13.6 m
GM	2.67	2.78	2.38	3.09 m

Table 2 . Response as a function of controller for the same seaway at 12 knots and 45 degrees.

Controller		Surge (m)	Sway (m)	Yaw (deg)
#1 human	Maximum	7.33	12.98	6.48
	Sig. Amp.	4.35	6.57	1.84
#2 human	Maximum	4.66	12.06	6.38
	Sig. Amp.	3.65	5.63	1.90
#3 human	Maximum	3.85	21.18	11.64
	Sig. Amp.	2.03	8.52	3.04
"Perfect" Autopilot	Maximum	4.64	3.92	2.49
	Sig. Amp.	2.63	7.02	0.78

Table 3. Autopilot coefficients used for different controllers.

	#1 human	#2 human	#3 human	"Perfect" Autopilot
Yaw gain	-1.16	-1.88	0.51	-7.81
Yaw rate gain	11.05	3.49	19.61	-8.50

Table 4. T-ADC(X) calm water turning predictions.

Speed (kn)	Advance (m)	Transfer (m)	Tactical Diameter (m)	Steady Diameter (m)
5	434.6	162.8	379.0	139.0
10	517.1	217.0	485.2	153.5
15	551.5	238.3	527.3	165.8
20	568.5	246.7	543.8	177.6

Table 5. Lateral response for different random seed values at 12 knots and worst heading.

	Surge (m)		Sway (m)		Yaw (deg)	
	Maximum	Sig. Amp.	Maximum	Sig. Amp	Maximum	Sig. Amp
Seed #1	45.7	27.7	28.7	19.8	15.0	5.1
Seed #2	95.5	59.7	31.1	14.5	16.1	4.9
Seed #3	56.3	39.9	25.6	14.5	13.4	4.6
Seed #4	45.2	32.7	24.9	14.7	15.4	5.3
Combined	95.5	38.4	31.1	15.7	16.1	5.0

Table 6. Lateral response for different random seed values at 12 knots and 135 degrees.

	Surge (m)		Sway (m)		Yaw (deg)	
	Maximum	Sig. Amp.	Maximum	Sig. Amp	Maximum	Sig. Amp
Seed #1	28.1	16.8	22.8	13.9	7.0	2.7
Seed #2	36.5	19.2	18.7	7.7	7.4	2.8
Seed #3	8.71	4.7	10.7	6.5	6.5	3.0
Seed #4	7.6	5.5	9.9	8.4	6.7	2.8
Combined	36.5	11.6	22.8	9.1	7.4	2.8

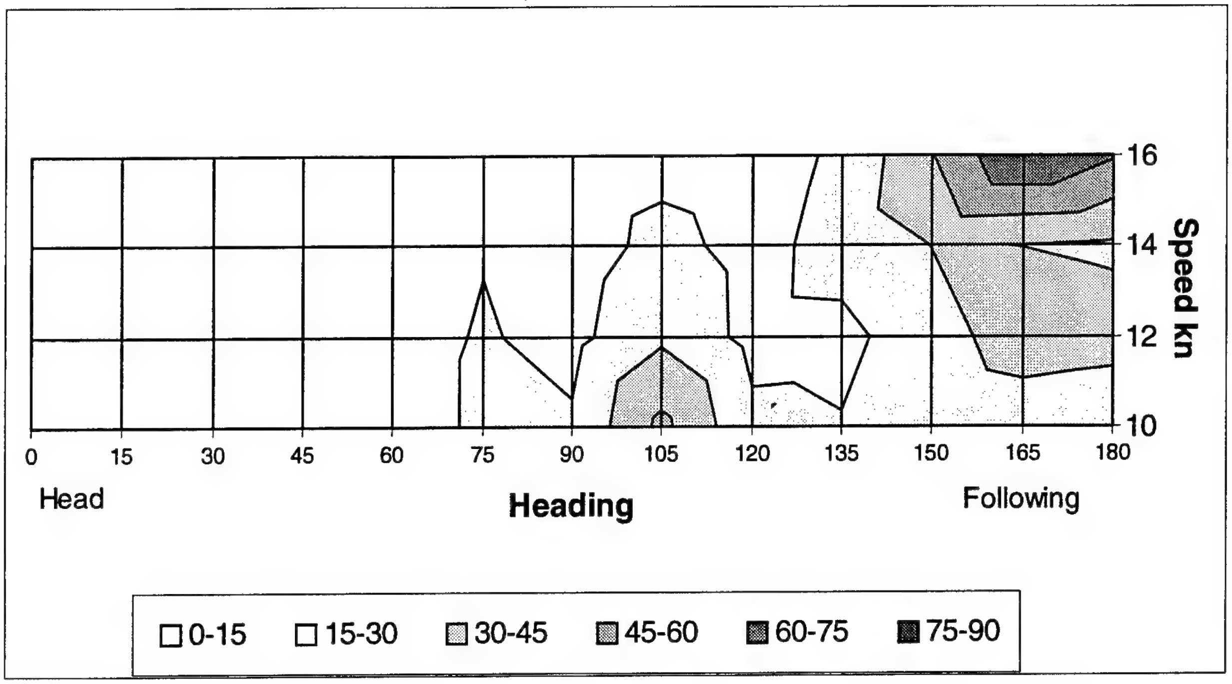

Figure 2. T-ADC(X) significant single amplitude surge (m) at UNREP speeds in high sea state 5.

Table 7. T-ADC(X) significant single amplitude surge (m) at UNREP speeds in high sea state 5.

	Head						Heading						Following
knots	0	15	30	45	60	75	90	105	120	135	150	165	180
10	11.22	11.34	9.68	8.03	11.33	16.32	16.80	48.91	18.17	15.76	16.37	20.74	18.00
12	8.02	7.98	6.24	5.77	8.96	16.22	11.00	27.45	10.85	11.56	22.84	38.42	35.85
14	5.43	5.76	4.63	4.98	7.00	14.27	7.99	19.32	10.20	20.33	30.34	29.93	27.64
16	2.39	2.47	3.15	4.93	6.80	11.31	6.34	10.64	7.16	17.80	44.39	75.30	61.17

Table 8. T-ADC(X) maximum surge (m) at UNREP speeds in high sea state 5.

	Head						Heading						Following
knots	0	15	30	45	60	75	90	105	120	135	150	165	180
10	29.22	28.77	23.75	21.19	23.77	34.09	34.42	99.47	43.43	36.76	45.42	50.56	44.02
12	19.80	19.77	16.20	17.92	23.26	34.98	17.07	53.68	30.14	36.46	50.43	82.98	95.50
14	13.36	13.28	10.68	15.79	20.80	29.89	14.49	37.88	24.60	38.58	80.53	57.42	49.72
16	7.77	7.67	8.98	14.09	20.16	28.62	11.52	30.99	21.57	36.12	66.17	145.06	117.62

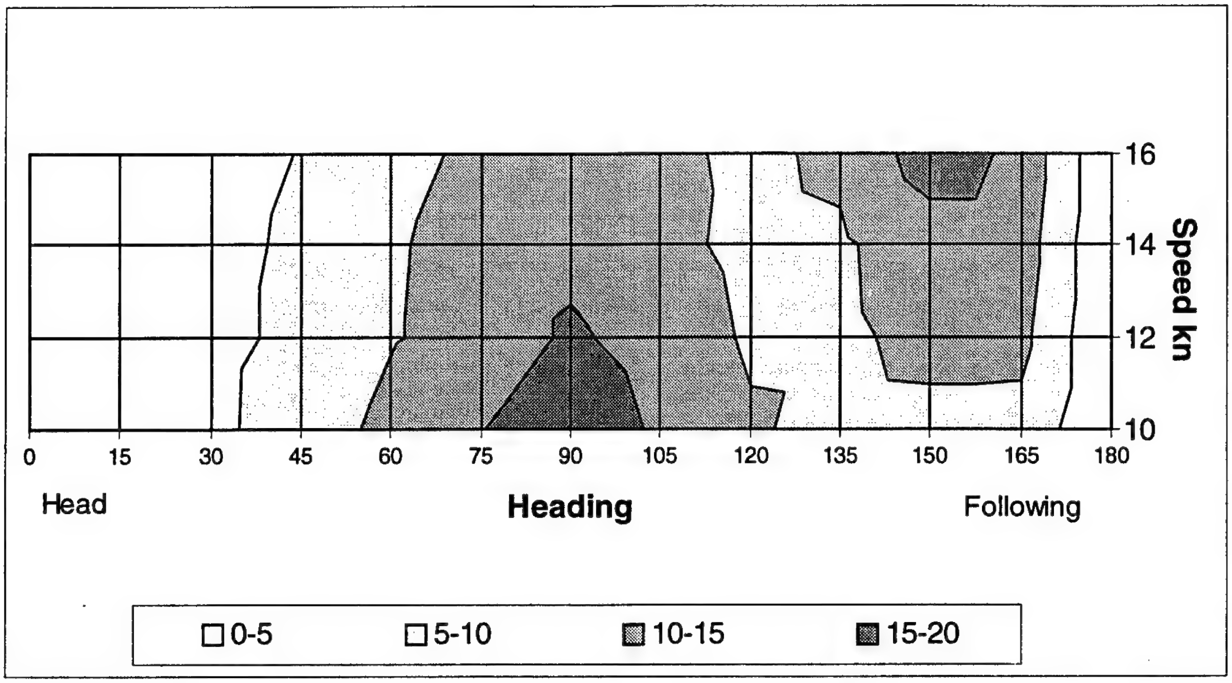

Figure 3. T-ADC(X) significant single amplitude sway (m) at UNREP speeds in high sea state 5.

Table 9. T-ADC(X) significant single amplitude sway (m) at UNREP speeds in high sea state 5.

	Head						Heading						Following
knots	0	15	30	45	60	75	90	105	120	135	150	165	180
10	0.00	1.80	3.96	7.31	11.33	14.79	18.22	14.29	10.55	8.60	8.74	8.56	0.00
12	0.00	1.65	3.81	6.00	9.65	12.13	15.70	13.00	9.34	9.14	11.28	11.31	0.00
14	0.00	1.50	3.36	6.01	9.46	12.10	13.66	11.46	8.65	9.34	12.58	12.57	0.00
16	0.00	1.44	2.97	5.19	7.84	11.48	11.76	11.10	8.98	10.96	17.40	13.93	0.00

Table 10. T-ADC(X) maximum sway (m) at UNREP speeds in high sea state 5.

	Head						Heading						Following
knots	0	15	30	45	60	75	90	105	120	135	150	165	180
10	0.00	4.83	9.44	17.39	28.23	36.55	34.06	29.09	22.02	24.22	17.04	15.07	0.00
12	0.00	4.29	8.13	14.89	24.68	31.10	28.85	26.87	21.45	22.79	20.98	15.31	0.00
14	0.00	3.87	7.34	13.12	21.20	25.57	26.63	26.10	20.88	23.29	23.24	24.38	0.00
16	0.00	3.43	7.11	12.45	18.16	25.95	23.56	24.66	20.66	19.37	34.49	26.36	0.00

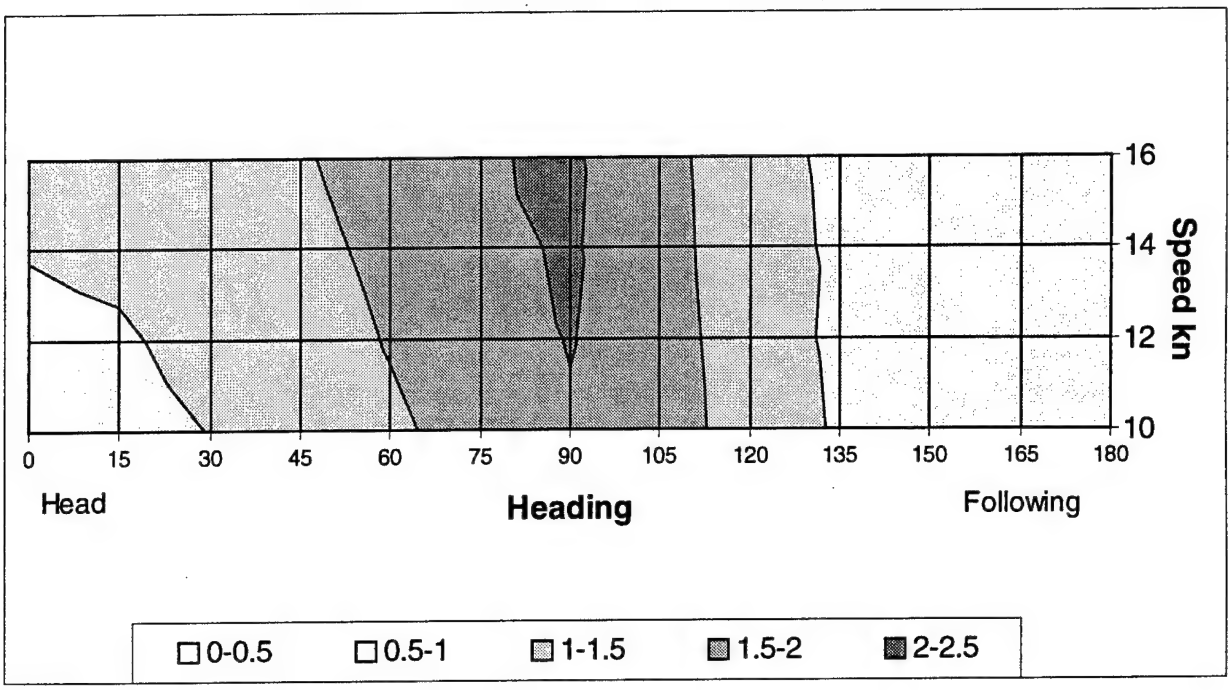

Figure 4. T-ADC(X) significant single amplitude heave (m) at UNREP speeds in high sea state 5.

Table 11. T-ADC(X) significant single amplitude heave (m) at UNREP speeds in high sea state 5.

	Head						Heading						Following
knots	0	15	30	45	60	75	90	105	120	135	150	165	180
10	0.89	0.91	1.01	1.18	1.42	1.70	1.96	1.76	1.28	0.95	0.75	0.65	0.61
12	0.94	0.97	1.08	1.28	1.53	1.81	2.02	1.72	1.24	0.92	0.74	0.65	0.62
14	1.01	1.05	1.16	1.36	1.62	1.89	2.05	1.69	1.21	0.93	0.74	0.64	0.61
16	1.11	1.14	1.25	1.46	1.71	1.97	2.07	1.67	1.18	0.91	0.74	0.63	0.60

Table 12. T-ADC(X) maximum heave (m) at UNREP speeds in high sea state 5.

	Head						Heading						Following
knots	0	15	30	45	60	75	90	105	120	135	150	165	180
10	1.56	1.55	1.97	2.19	2.61	3.25	3.58	3.66	2.77	2.01	1.46	1.24	1.28
12	1.78	1.78	1.96	2.34	2.64	3.25	3.80	3.38	2.72	1.70	1.30	1.18	1.03
14	1.97	2.07	2.14	2.52	2.93	3.17	3.78	3.56	2.83	1.91	1.32	1.15	1.00
16	2.08	2.28	2.37	2.45	3.14	3.44	3.84	3.84	2.03	2.14	1.38	1.00	0.97

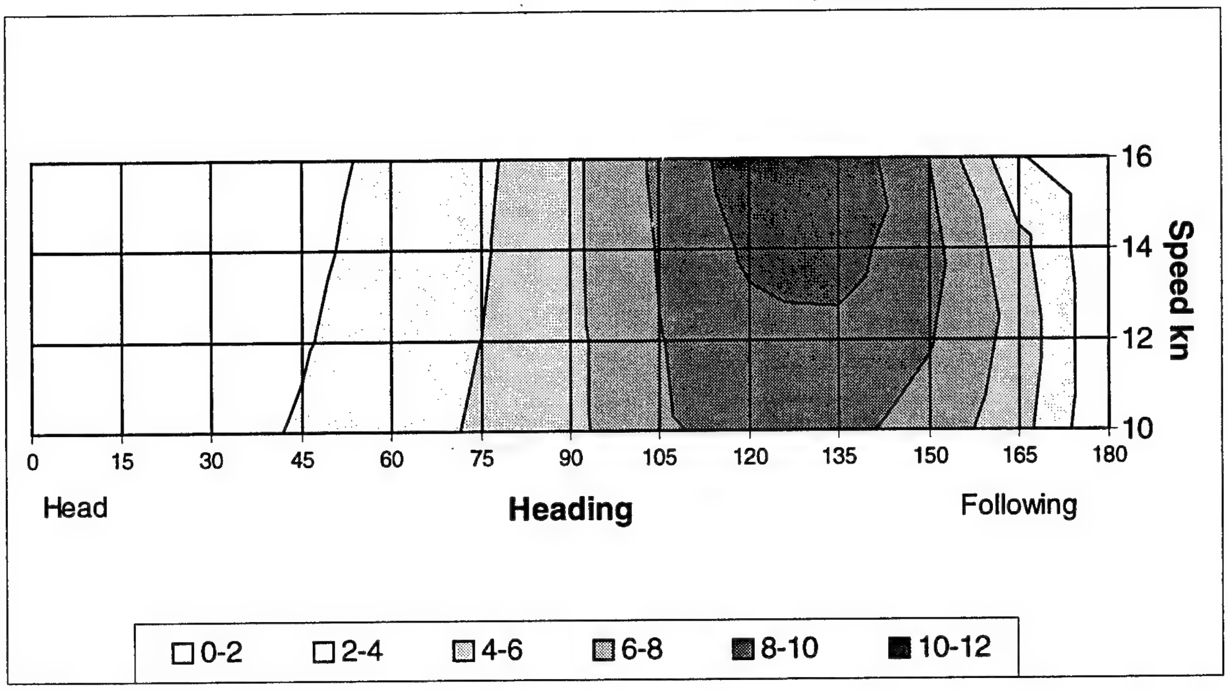

Figure 5. T-ADC(X) significant single amplitude roll (deg) at UNREP speeds in high sea state 5.

Table 13. T-ADC(X) significant single amplitude roll (deg) at UNREP speeds in high sea state 5.

	Head						Heading						Following
knots	0	15	30	45	60	75	90	105	120	135	150	165	180
10	0.02	0.65	1.39	2.17	3.16	4.25	5.54	7.73	8.71	8.56	7.21	4.70	0.04
12	0.03	0.53	1.13	1.87	2.85	4.01	5.55	7.93	9.47	9.54	8.15	5.20	0.04
14	0.04	0.45	0.98	1.65	2.58	3.81	5.59	8.14	10.32	10.79	8.67	4.58	0.04
16	0.03	0.39	0.87	1.49	2.38	3.61	5.53	8.42	11.15	11.59	7.96	2.17	0.04

Table 14. T-ADC(X) maximum roll (deg) at UNREP speeds in high sea state 5.

	Head						Heading						Following
knots	0	15	30	45	60	75	90	105	120	135	150	165	180
10	0.06	1.47	2.74	3.93	5.86	7.78	10.75	14.95	16.61	14.6	10.93	8.56	0.08
12	0.07	1.01	2.15	3.97	4.82	7.09	10.67	14.49	17.14	13.81	12.39	9.71	0.07
14	0.06	0.92	1.97	3.25	5.34	6.87	10.58	14.92	17.69	17.11	13.47	8.62	0.07
16	0.06	0.86	1.79	3	4.6	6.48	9.55	15.15	16.89	19.54	14.55	4.37	0.08

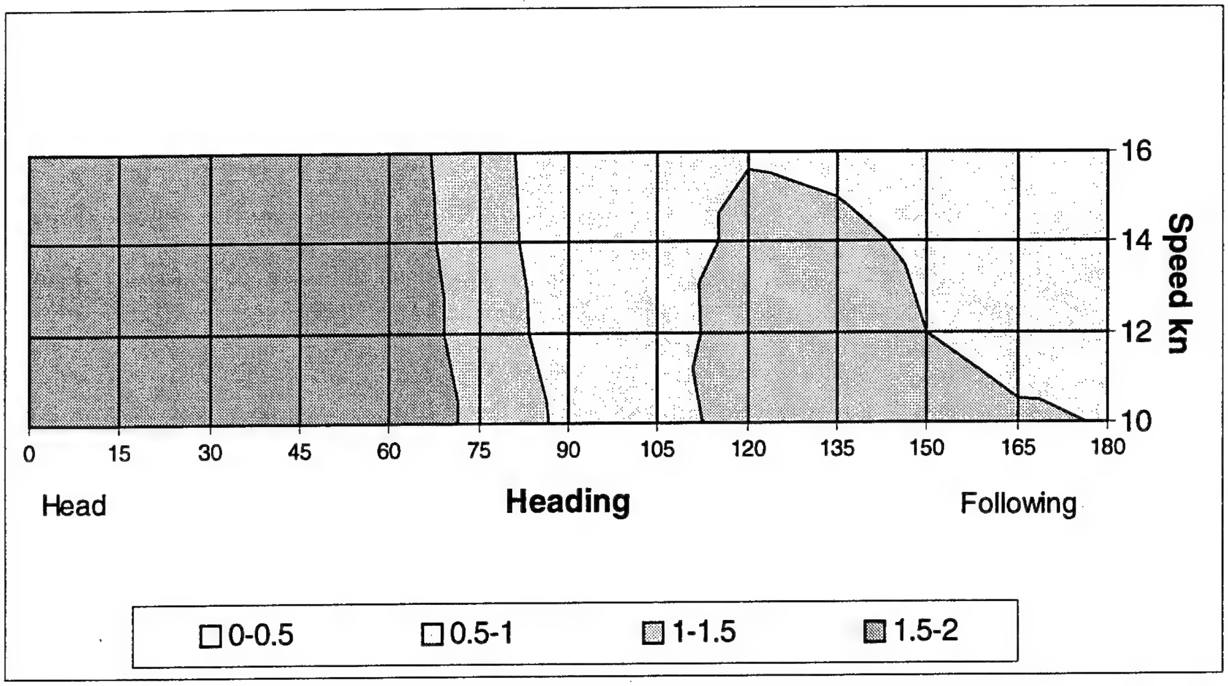

Figure 6. T-ADC(X) significant single amplitude pitch (deg) at UNREP speeds in high sea state 5.

Table 15. T-ADC(X) significant single amplitude pitch (deg) at UNREP speeds in high sea state 5.

	Head						Heading						Following
knots	0	15	30	45	60	75	90	105	120	135	150	165	180
10	1.57	1.59	1.65	1.69	1.66	1.45	0.87	0.88	1.13	1.12	1.06	1.02	1.00
12	1.62	1.63	1.68	1.72	1.66	1.40	0.69	0.92	1.10	1.08	1.00	0.96	0.96
14	1.65	1.66	1.71	1.73	1.66	1.35	0.58	0.92	1.04	1.03	0.98	0.95	0.92
16	1.67	1.68	1.72	1.74	1.65	1.32	0.52	0.92	0.99	0.97	0.92	0.87	0.84

Table 16. T-ADC(X) maximum pitch (deg) at UNREP speeds in high sea state 5.

	Head						Heading						Following
knots	0	15	30	45	60	75	90	105	120	135	150	165	180
10	2.71	2.84	2.86	3.06	2.96	2.63	1.81	1.90	2.69	2.39	1.95	1.89	1.84
12	2.76	2.75	2.82	2.96	2.82	2.41	1.43	2.07	2.18	1.94	2.01	1.81	1.60
14	2.99	3.15	3.09	3.04	3.13	2.44	1.24	1.88	2.21	1.94	1.79	1.87	1.82
16	3.16	3.18	3.26	2.96	2.88	2.44	1.16	2.04	2.20	2.19	1.71	1.70	1.60

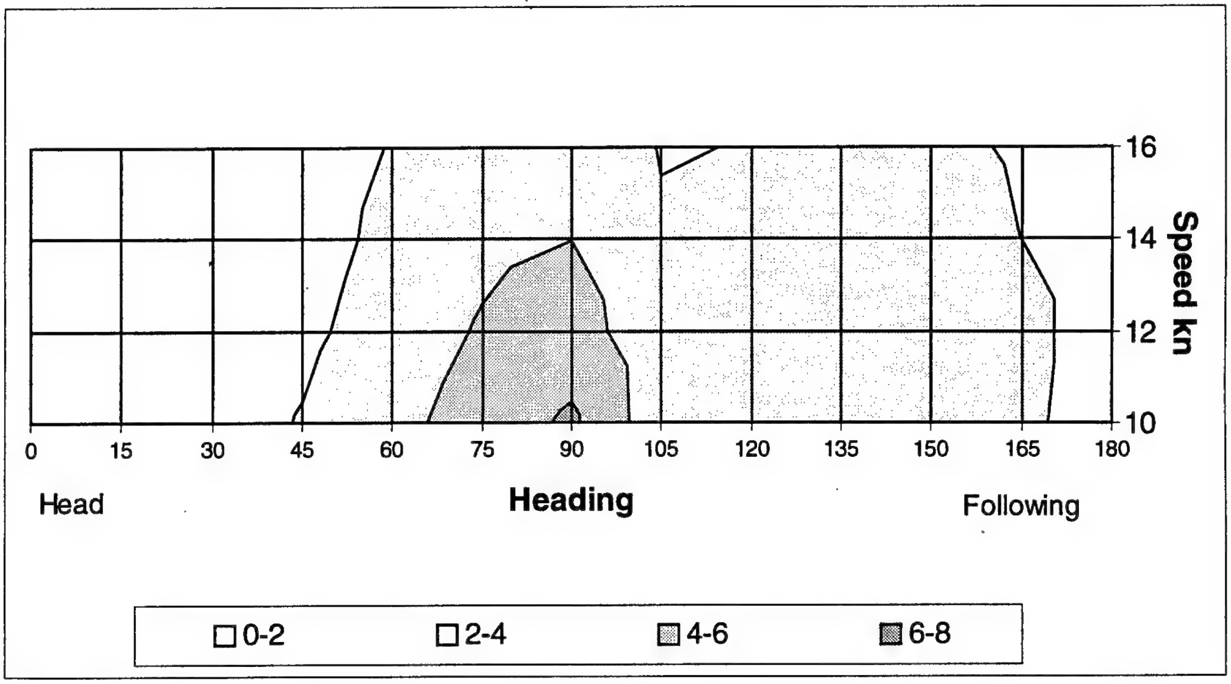

Figure 7. T-ADC(X) significant single amplitude yaw (deg) at UNREP speeds in high sea state 5.

Table 17. T-ADC(X) significant single amplitude yaw (deg) at UNREP speeds in high sea state 5.

	Head						Heading						Following
knots	0	15	30	45	60	75	90	105	120	135	150	165	180
10	0.08	0.47	1.14	2.10	3.40	4.94	6.30	2.75	3.17	3.14	3.38	2.85	0.05
12	0.04	0.38	0.83	1.63	2.80	4.19	4.95	2.58	2.41	2.81	3.45	3.08	0.01
14	0.03	0.34	0.69	1.33	2.42	3.58	3.99	2.25	2.22	2.97	3.22	1.98	0.00
16	0.03	0.32	0.60	1.16	2.10	3.08	3.27	1.89	2.07	2.85	2.61	1.71	0.01

Table 18. T-ADC(X) maximum yaw (deg) at UNREP speeds in high sea state 5.

	Head						Heading						Following
knots	0	15	30	45	60	75	90	105	120	135	150	165	180
10	0.19	1.71	3.8	7.09	12.22	18.32	20.46	9.94	9.07	11.05	9.01	8.15	0.12
12	0.09	1.49	2.88	5.57	10	14.56	16.12	8.22	7.84	7.42	11.17	7.74	0.02
14	0.05	1.38	2.74	4.61	8.09	11.8	13.29	8.32	8.02	7.82	7.8	6.86	0.01
16	0.06	1.28	2.13	3.88	6.82	9.66	10.67	6.28	6.82	7.26	9.1	3.21	0.02

Table 19. Significant single amplitude surge (m) for seed #2 at worst heading by sea state.

	10 kn	12 kn	14 kn	16 kn
Low Sea State 5	24.71	19.58	16.36	34.04
Mid Sea State 5	42.89	32.25	37.31	39.96
High Sea State 5	60.14	59.66	27.85	80.57

Table 20. Significant single amplitude sway (m) for seed #2 at worst heading by sea state.

	10 kn	12 kn	14 kn	16 kn
Low Sea State 5	9.53	7.82	6.87	11.94
Mid Sea State 5	13.77	12.85	10.37	12.96
High Sea State 5	18.43	14.47	13.64	22.15

Table 21. Significant single amplitude yaw (deg) for seed #2 at worst heading by sea state.

	10 kn	12 kn	14 kn	16 kn
Low Sea State 5	2.68	2.04	1.66	1.40
Mid Sea State 5	4.60	3.58	2.80	2.36
High Sea State 5	6.52	4.88	3.88	3.14

Table 22. T-ADC(X) significant single amplitude surge (m) at UNREP speeds in low sea state 5.

	Head						Heading						Following
knots	0	15	30	45	60	75	90	105	120	135	150	165	180
10	2.47	2.59	1.17	4.25	9.04	13.88	8.61	24.71	10.10	10.14	9.27	9.00	20.40
12	1.57	1.59	2.02	4.93	8.11	12.82	6.43	15.49	7.19	6.28	10.85	19.58	17.55
14	1.40	1.78	2.47	4.19	6.42	10.03	4.77	10.83	6.54	9.49	6.92	16.36	10.11
16	0.84	1.03	2.25	3.96	5.29	7.32	3.31	7.46	5.59	17.46	18.00	28.27	34.04

Table 23. T-ADC(X) absolute maximum surge (m) at UNREP speeds in low sea state 5.

	Head						Heading						Following
knots	0	15	30	45	60	75	90	105	120	135	150	165	180
10	2.62	2.70	2.01	6.68	14.23	21.60	12.48	39.11	17.41	15.30	14.68	14.46	22.16
12	2.18	2.57	4.27	8.71	13.54	19.86	9.53	26.45	12.71	14.67	21.58	27.02	27.97
14	1.71	2.29	4.57	7.57	11.32	14.50	7.85	17.24	10.64	16.23	12.35	17.09	13.42
16	1.76	1.98	3.93	6.94	9.92	11.61	5.45	12.95	9.98	14.45	34.46	42.31	55.89

Table 24. T-ADC(X) significant single amplitude sway (m) at UNREP speeds in low sea state 5.

knots	Head 0	15	30	45	60	75	Heading 90	105	120	135	150	165	Following 180
10	0.00	1.34	2.17	3.99	7.79	8.59	9.53	7.43	5.52	3.90	3.39	3.32	0.00
12	0.00	1.57	2.52	3.18	5.73	7.59	7.82	6.01	5.21	3.93	5.61	4.18	0.00
14	0.00	1.47	2.62	3.30	4.56	6.33	6.87	5.00	4.37	3.63	5.39	5.62	0.00
16	0.00	1.22	2.02	3.24	4.41	5.27	5.62	4.96	5.35	5.12	11.94	6.32	0.00

Table 25. T-ADC(X) absolute maximum sway (m) at UNREP speeds in low sea state 5.

knots	Head 0	15	30	45	60	75	Heading 90	105	120	135	150	165	Following 180
10	0.00	2.94	5.00	7.95	12.90	17.14	14.27	8.72	6.52	7.30	8.43	3.53	0.00
12	0.00	2.73	4.51	7.00	11.49	14.63	12.25	9.06	6.04	7.57	8.44	8.04	0.00
14	0.00	2.67	4.09	6.44	9.83	12.86	10.77	7.81	8.04	9.47	9.30	6.29	0.00
16	0.00	2.41	4.01	5.85	8.14	10.85	9.73	7.58	8.33	10.57	13.92	7.89	0.00

Table 26. T-ADC(X) significant single amplitude yaw (deg) at UNREP speeds in low sea state 5.

knots	Head 0	15	30	45	60	75	Heading 90	105	120	135	150	165	Following 180
10	0.08	0.32	0.40	0.84	1.62	2.46	2.68	1.20	1.26	1.28	1.40	1.28	0.00
12	0.04	0.32	0.36	0.66	1.42	1.96	2.04	1.02	0.80	1.20	1.80	1.40	0.00
14	0.02	0.30	0.34	0.52	1.22	1.66	1.60	0.78	0.86	1.50	1.56	0.70	0.00
16	0.04	0.30	0.32	0.50	1.02	1.36	1.26	0.66	0.94	1.40	1.10	1.36	0.00

Table 27. T-ADC(X) absolute maximum yaw (deg) at UNREP speeds in low sea state 5.

knots	Head 0	15	30	45	60	75	Heading 90	105	120	135	150	165	Following 180
10	0.09	1.15	1.50	2.87	5.54	8.38	8.43	4.28	3.71	2.94	3.26	2.40	0.02
12	0.05	1.10	1.39	2.24	4.53	6.57	6.37	3.16	2.64	2.99	3.71	2.20	0.01
14	0.02	1.09	1.33	1.90	3.67	5.37	5.29	2.74	2.28	3.35	3.79	1.80	0.00
16	0.04	1.09	1.33	1.81	3.19	4.32	4.58	2.93	2.89	3.23	2.06	2.09	0.00

Table 28. T-ADC(X) significant single amplitude surge (m) at UNREP speeds in middle sea state 5.

knots	Head 0	15	30	45	60	75	Heading 90	105	120	135	150	165	Following 180
10	4.98	5.04	2.10	4.24	11.87	19.09	12.11	42.88	16.89	14.06	12.25	19.25	12.50
12	2.29	2.36	2.49	6.05	10.80	18.49	8.27	25.92	9.43	12.12	26.02	26.27	32.25
14	1.71	2.29	2.99	5.52	8.59	15.26	6.43	18.81	8.91	11.81	37.31	18.71	28.26
16	1.09	1.37	2.86	5.52	7.08	12.32	5.61	11.94	8.21	11.02	18.98	39.96	38.76

Table 29. T-ADC(X) absolute maximum surge (m) at UNREP speeds in middle sea state 5.

	Head						Heading						Following
knots	0	15	30	45	60	75	90	105	120	135	150	165	180
10	5.65	5.85	2.80	6.57	17.73	30.23	16.27	68.63	27.70	19.05	23.52	25.88	21.06
12	2.45	3.26	4.69	10.87	17.27	27.15	10.67	42.54	17.19	21.70	33.12	37.92	49.19
14	1.88	2.39	5.40	9.93	15.62	22.28	8.84	31.38	14.87	22.94	40.95	23.97	36.99
16	1.87	2.29	4.99	9.39	13.98	19.75	7.79	21.05	14.08	24.43	37.78	55.58	58.68

Table 30. T-ADC(X) significant single amplitude sway (m) at UNREP speeds in middle sea state 5.

	Head						Heading						Following
knots	0	15	30	45	60	75	90	105	120	135	150	165	180
10	0.00	1.48	3.02	5.66	11.03	12.09	13.77	10.42	8.27	5.51	5.52	4.62	0.00
12	0.00	1.74	3.56	4.66	8.45	12.85	11.39	9.78	8.06	4.78	5.74	7.88	0.00
14	0.00	1.64	3.52	4.96	6.94	8.78	9.67	8.85	5.49	4.79	10.37	9.53	0.00
16	0.00	1.34	2.55	4.98	6.61	8.14	8.92	7.77	6.43	5.82	12.32	12.96	0.00

Table 31. T-ADC(X) absolute maximum sway (m) at UNREP speeds in middle sea state 5.

	Head						Heading						Following
knots	0	15	30	45	60	75	90	105	120	135	150	165	180
10	0.00	3.49	6.47	11.54	19.28	24.81	23.33	12.61	10.65	9.91	11.46	5.82	0.00
12	0.00	3.27	5.95	10.12	17.16	19.98	19.52	12.84	8.70	11.87	8.66	12.89	0.00
14	0.00	3.12	5.43	9.34	14.51	18.37	16.64	11.71	10.84	11.58	16.51	9.69	0.00
16	0.00	2.83	5.11	8.65	12.35	15.77	14.26	12.59	9.53	12.18	28.89	17.86	0.00

Table 32. T-ADC(X) significant single amplitude yaw (deg) at UNREP speeds in middle sea state 5.

	Head						Heading						Following
knots	0	15	30	45	60	75	90	105	120	135	150	165	180
10	0.02	0.34	0.58	1.38	2.46	3.78	4.60	1.88	2.26	1.66	1.84	1.66	0.04
12	0.02	0.34	0.48	1.06	2.16	3.18	3.58	1.74	1.38	1.80	2.54	2.22	0.00
14	0.06	0.30	0.44	0.86	1.90	2.68	2.80	1.48	1.26	1.84	2.58	1.30	0.00
16	0.02	0.28	0.40	0.82	1.66	2.22	2.36	1.20	1.42	1.90	1.72	1.56	0.00

Table 33. T-ADC(X) absolute maximum yaw (deg) at UNREP speeds in middle sea state 5.

	Head						Heading						Following
knots	0	15	30	45	60	75	90	105	120	135	150	165	180
10	0.02	1.23	2.20	4.43	8.39	13.10	13.86	7.00	5.99	4.44	5.00	4.08	0.08
12	0.05	1.18	1.74	3.47	6.92	10.43	10.66	5.37	4.09	4.67	6.42	4.50	0.01
14	0.05	1.17	1.61	2.73	5.58	8.61	8.38	4.46	3.39	4.37	5.79	2.11	0.01
16	0.04	1.14	1.59	2.55	4.72	6.79	6.84	4.23	4.41	4.75	3.24	2.38	0.00

Table 34. Significant single amplitude surge (m) for seed #2 at worst heading by rudder size in high sea state 5.

	10 kn	12 kn	14 kn	16 kn
Original rudder	60.14	59.66	27.85	80.57
+20% increase	48.74	59.59	30.15	80.57

Table 35. Significant single amplitude sway (m) for seed #2 at worst heading by rudder size in high sea state 5.

	10 kn	12 kn	14 kn	16 kn
Original rudder	18.43	14.47	13.64	22.15
+20% increase	15.66	14.13	11.47	19.76

Table 36. Significant single amplitude yaw (deg) for seed #2 at worst heading by rudder size in high sea state 5.

	10 kn	12 kn	14 kn	16 kn
Original rudder	6.52	4.88	3.88	3.14
+20% increase	5.00	3.96	3.06	2.58

Table 37. T-ADC(X) significant single amplitude surge (m) at UNREP speeds in high sea state 5 with 20% increased rudder area.

	Head						Heading						Following
knots	0	15	30	45	60	75	90	105	120	135	150	165	180
10	4.78	4.70	3.80	7.99	18.11	23.64	17.13	48.74	24.57	18.17	22.50	26.73	27.65
12	3.85	3.80	5.23	10.25	15.07	23.33	9.43	32.30	14.43	18.12	30.36	56.98	59.69
14	3.43	4.54	5.93	9.13	12.19	19.78	6.65	23.29	15.29	25.16	30.15	24.15	16.42
16	2.24	2.83	5.32	8.67	11.07	16.97	5.71	14.25	11.12	28.79	52.99	51.88	80.57

Table 38. T-ADC(X) absolute maximum surge (m) at UNREP speeds in high sea state 5 with 20% increased rudder area.

	Head						Heading						Following
knots	0	15	30	45	60	75	90	105	120	135	150	165	180
10	6.32	5.88	7.23	12.90	24.26	35.73	24.07	80.27	42.45	34.09	42.35	44.67	44.01
12	5.81	6.59	10.07	18.07	23.18	34.60	14.19	52.68	29.51	34.42	46.17	85.50	95.59
14	5.25	5.98	10.42	15.93	21.53	30.16	10.49	41.69	23.67	42.67	29.30	53.88	35.32
16	3.51	4.49	9.17	14.32	19.96	24.81	7.88	25.37	21.29	51.29	66.78	57.11	96.46

Table 39. T-ADC(X) significant single amplitude sway (m) at UNREP speeds in high sea state 5 with 20% increased rudder area.

	Head						Heading						Following
knots	0	15	30	45	60	75	90	105	120	135	150	165	180
10	0.00	1.97	4.11	7.47	13.93	15.66	14.87	11.46	10.19	8.21	10.29	7.94	0.00
12	0.00	2.18	4.66	6.18	10.65	14.13	12.78	10.79	11.45	9.37	8.91	11.41	0.00
14	0.00	2.02	4.79	6.79	8.73	11.47	10.86	9.53	7.69	7.41	9.58	10.76	0.00
16	0.00	1.59	3.20	6.50	8.08	10.46	10.19	9.03	8.55	8.87	19.76	16.62	0.00

Table 40. T-ADC(X) absolute maximum sway (m) at UNREP speeds in high sea state 5 with 20% increased rudder area.

	Head						Heading						Following
knots	0	15	30	45	60	75	90	105	120	135	150	165	180
10	0.00	4.91	8.86	16.07	25.53	31.76	29.34	15.93	14.42	14.60	17.73	10.13	0.00
12	0.00	4.21	7.72	13.60	22.40	26.36	25.11	15.56	13.39	20.64	14.97	21.31	0.00
14	0.00	3.71	7.05	12.30	19.29	22.82	21.85	12.41	16.50	21.15	16.22	18.88	0.00
16	0.00	3.48	6.71	11.58	16.47	19.87	19.15	15.73	15.96	19.32	22.39	26.18	0.00

Table 41. T-ADC(X) significant single amplitude yaw (deg) at UNREP speeds in high sea state 5 with 20% increased rudder area.

	Head						Heading						Following
knots	0	15	30	45	60	75	90	105	120	135	150	165	180
10	0.10	0.38	0.86	1.78	2.94	4.30	5.00	2.10	2.68	2.66	2.88	2.68	0.02
12	0.02	0.34	0.64	1.34	2.52	3.62	3.96	1.76	1.96	2.56	3.32	2.30	0.00
14	0.02	0.30	0.56	1.06	2.14	3.02	3.06	1.56	1.82	2.52	2.50	1.64	0.00
16	0.02	0.28	0.48	0.98	1.84	2.44	2.58	1.34	1.92	2.28	2.14	1.42	0.00

Table 42. T-ADC(X) absolute maximum yaw (deg) at UNREP speeds in high sea state 5 with 20% increased rudder area.

	Head						Heading						Following
knots	0	15	30	45	60	75	90	105	120	135	150	165	180
10	0.16	1.45	3.18	6.13	10.77	16.01	16.10	8.05	7.38	6.02	7.82	6.86	0.02
12	0.05	1.31	2.45	4.71	8.77	12.57	12.56	5.95	5.92	6.54	9.69	5.46	0.01
14	0.05	1.26	1.93	3.55	6.81	10.08	10.08	5.14	5.20	5.99	5.00	3.43	0.01
16	0.03	1.20	1.72	3.09	5.56	7.91	8.26	5.18	5.02	6.07	6.79	2.89	0.00

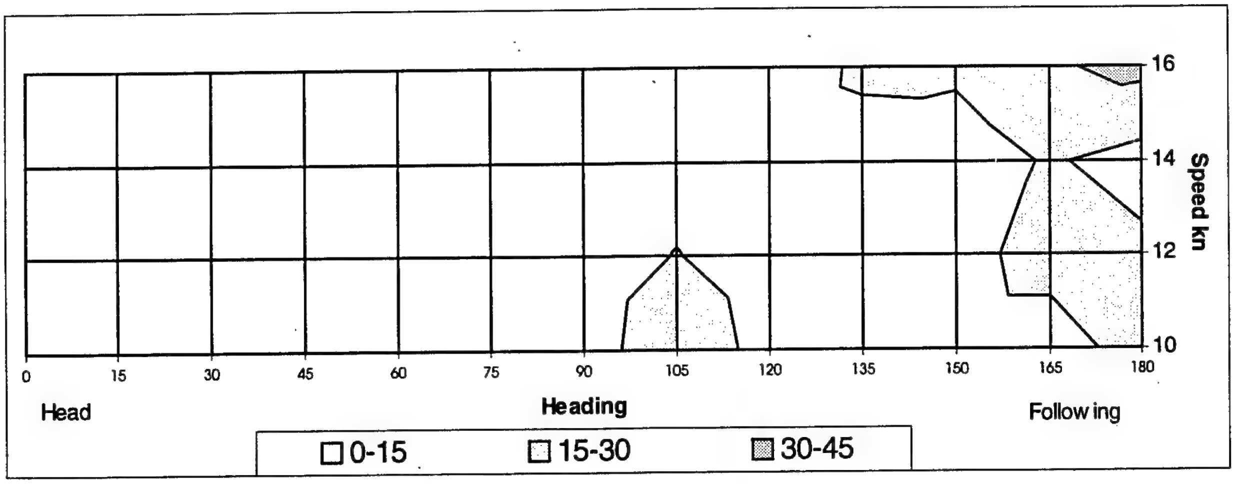

Figure 8 T-ADC(X) sig. sin. amp. surge (m) in low sea state 5 (seed #2).

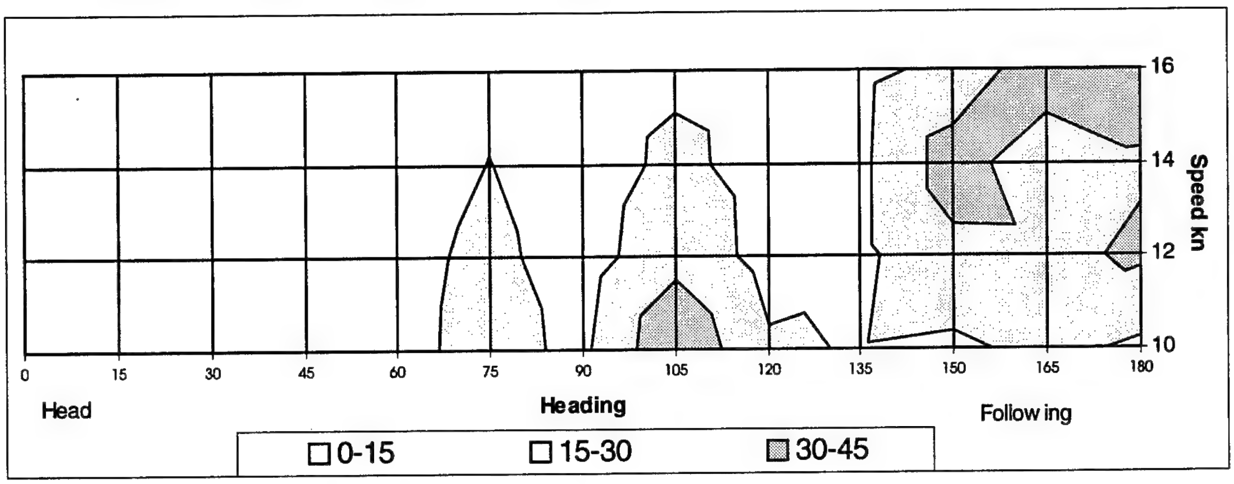

Figure 9 T-ADC(X) sig. sin. amp. surge (m) in medium sea state 5 (seed #2).

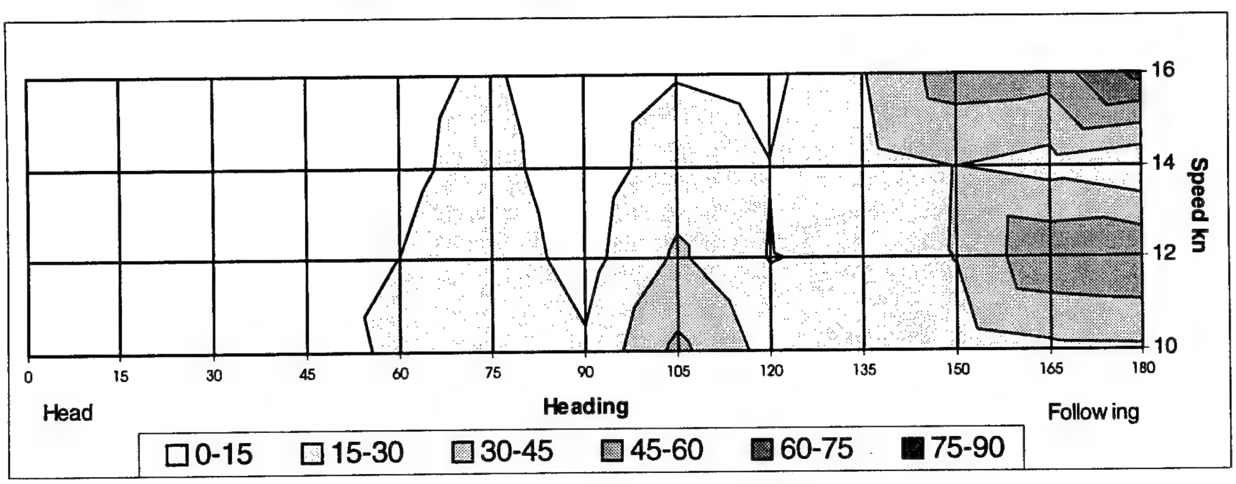

Figure 10 T-ADC(X) sig. sin. amp. surge (m) in high sea state 5 (seed #2) + 20% larger rudder.

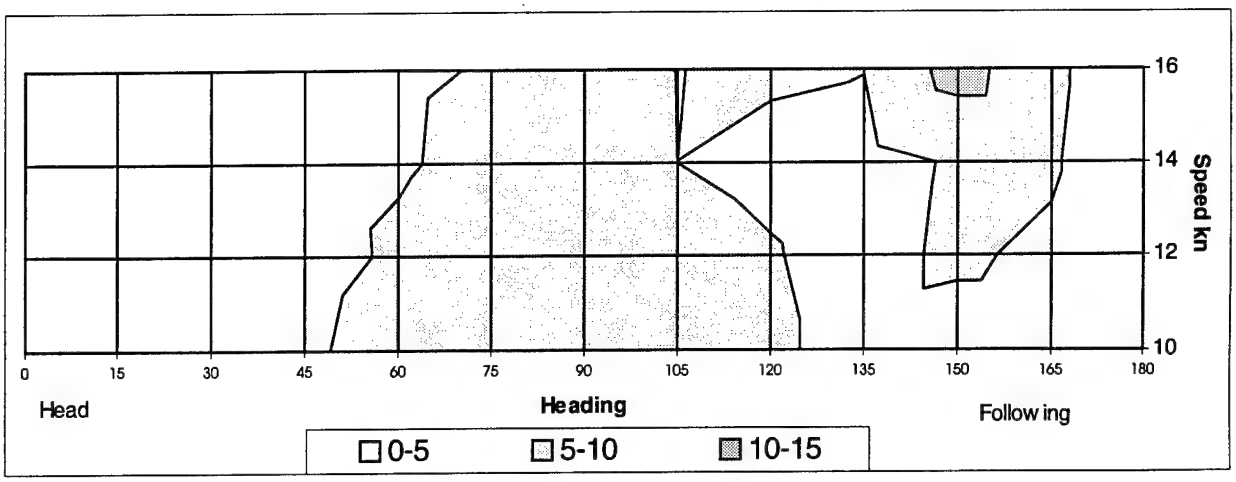

Figure 11 T-ADC(X) sig. sin. amp. sway (m) in low sea state 5 (seed #2)

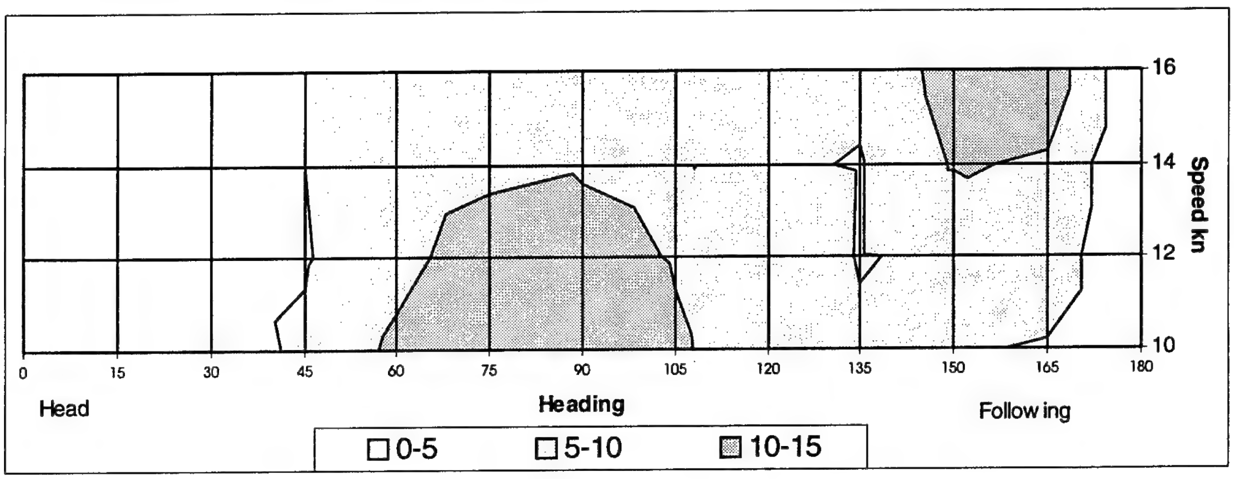

Figure 12 T-ADC(X) sig. sin. amp. sway (m) in medium sea state 5 (seed #2).

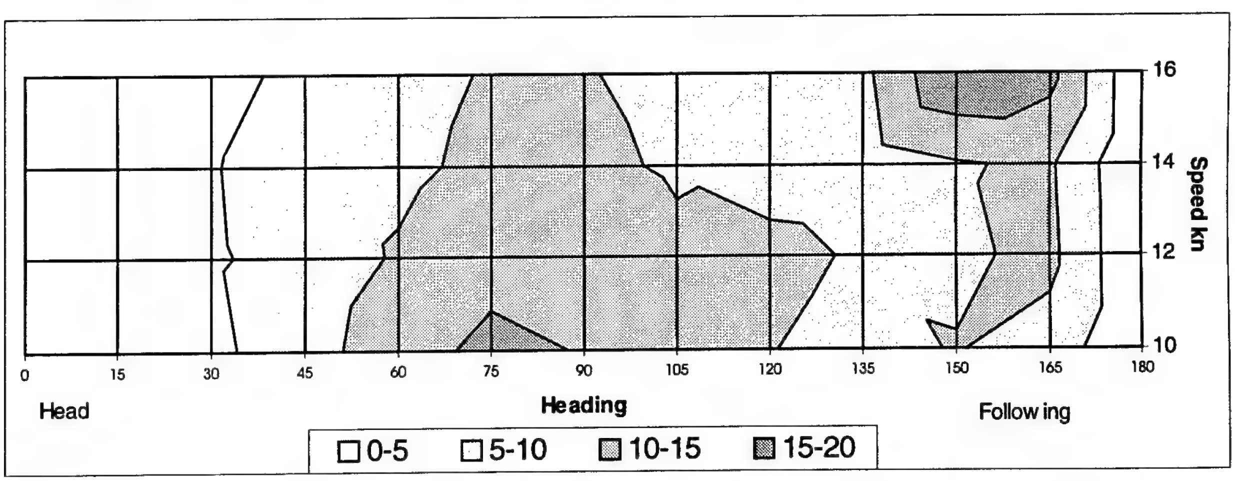

Figure 13 T-ADC(X) sig. sin. amp. sway (m) in high sea state 5 (seed #2) + 20% larger rudder.

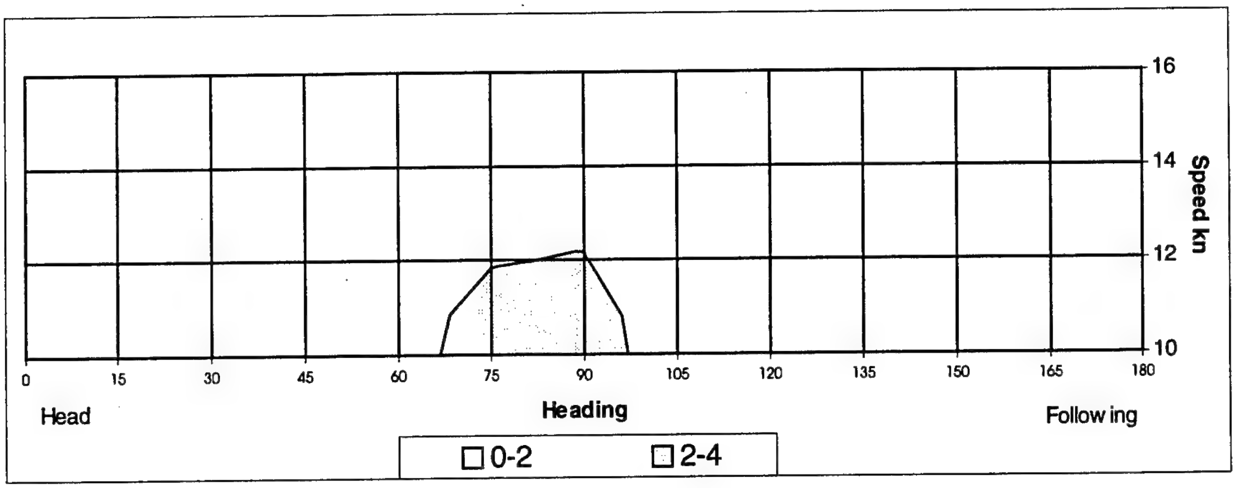

Figure 14 T-ADC(X) sig. sin. amp. yaw (deg) in low sea state 5 (seed #2).

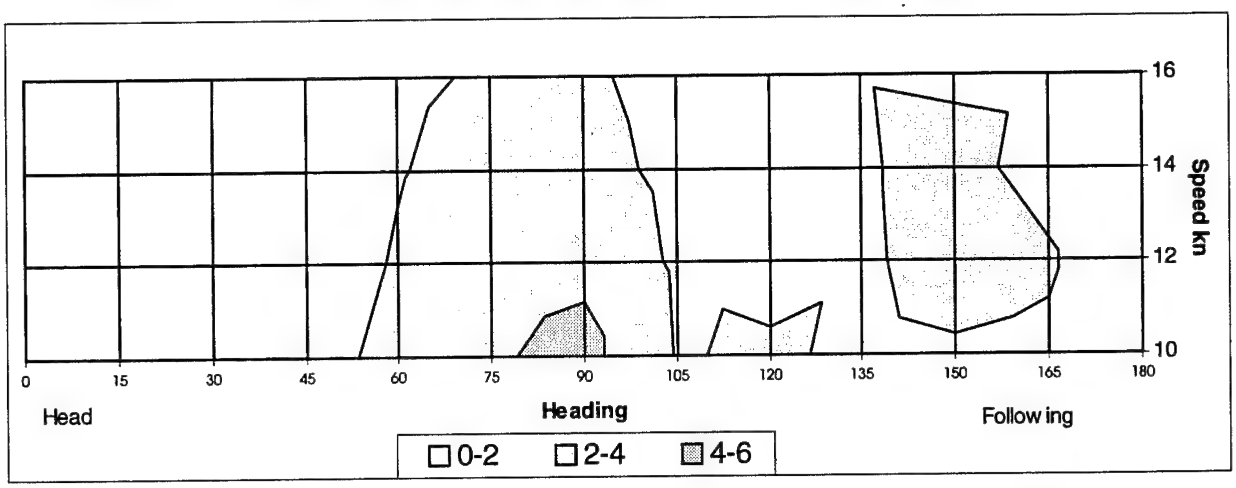

Figure 15 T-ADC(X) sig. sin. amp. yaw (deg) in medium sea state 5 (seed #2).

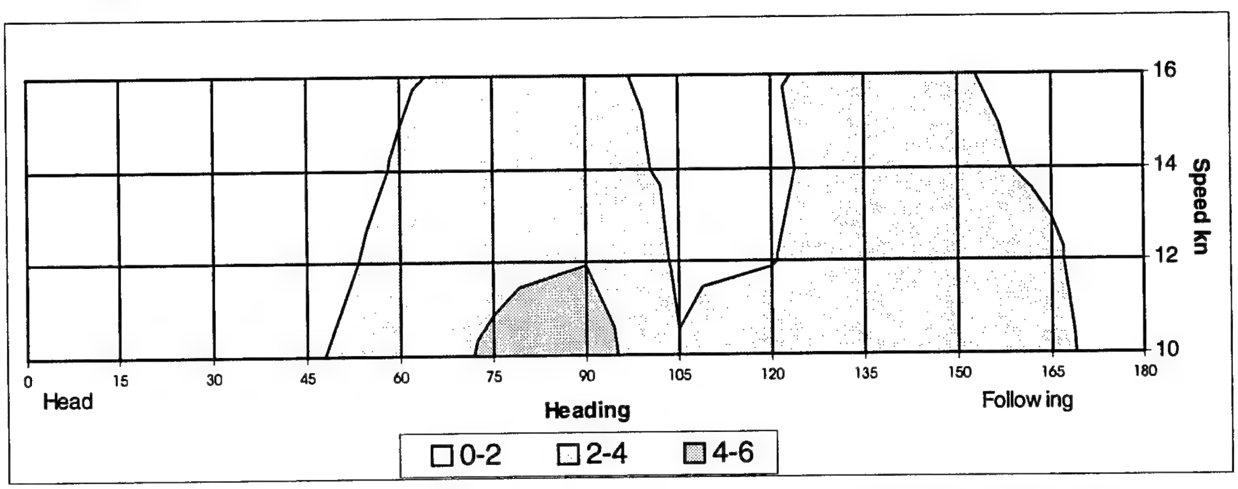

Figure 16 T-ADC(X) sig. sin. amp. yaw (deg) in high sea state 5 (seed #2) + 20% larger rudder.

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